Monte Carlo implementation of Jet Modification

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- I will deal with the current status of JETSCAPE,
- Most of what I will discuss is currently already in the JETSCAPE framework
- I will talk about mostly MATTER, some MARTINI, mention the word AdS/CFT
- Present the current setup, and what is included.

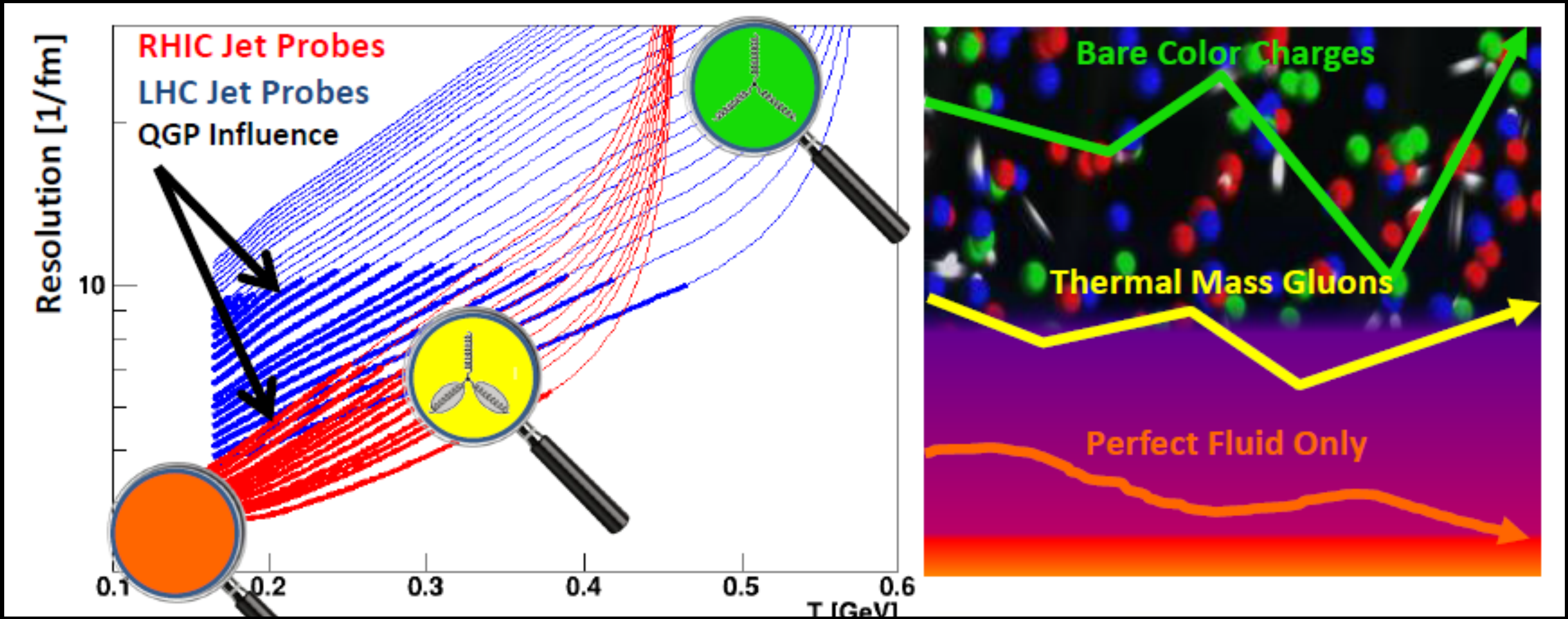
Scale dependence: of probe and target

The medium looks different at different length scales

The probe behaves differently at different scales

Need a comprehensive tool to study QGP with jets

From the 2015 LRP



Jets in a medium, grand picture

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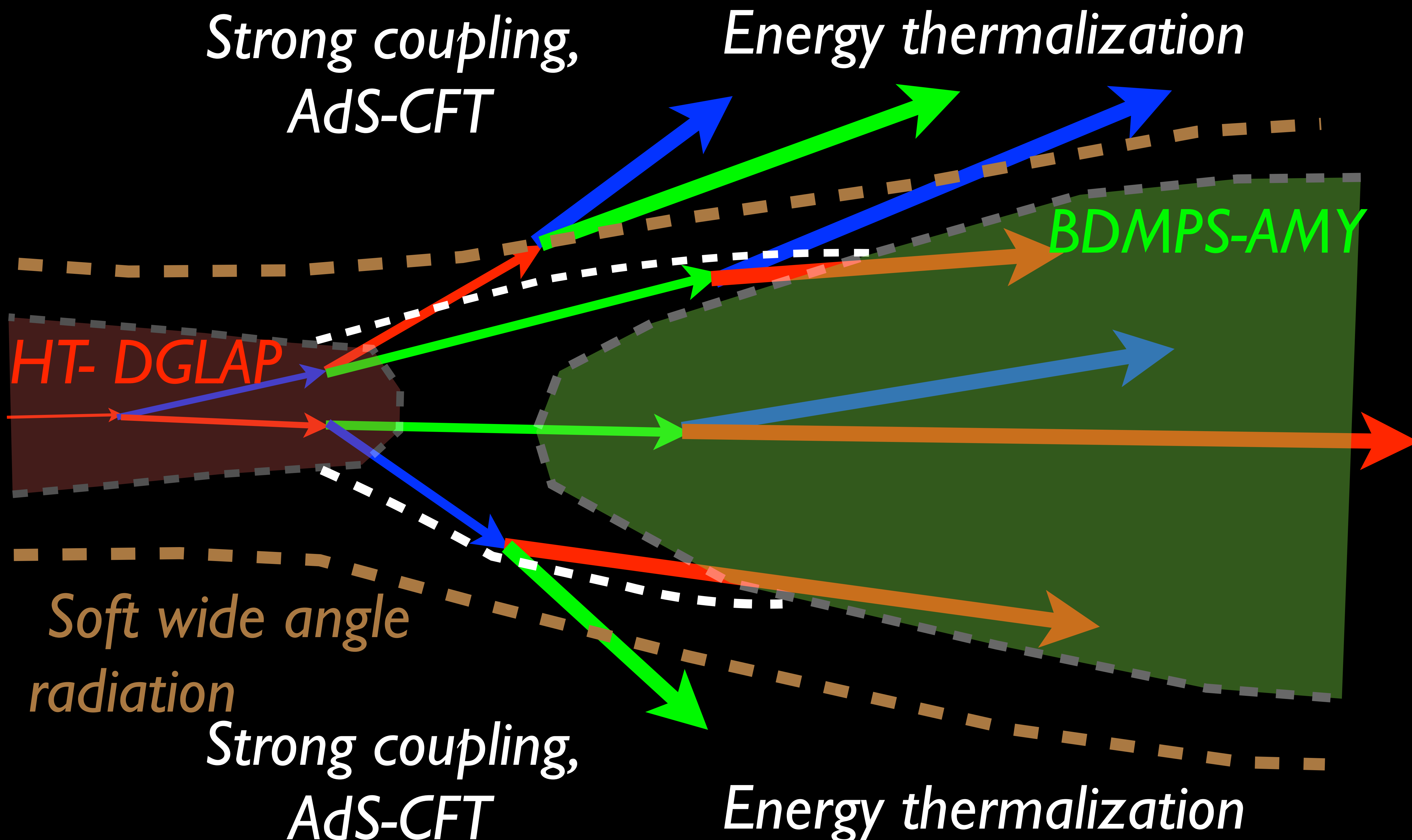
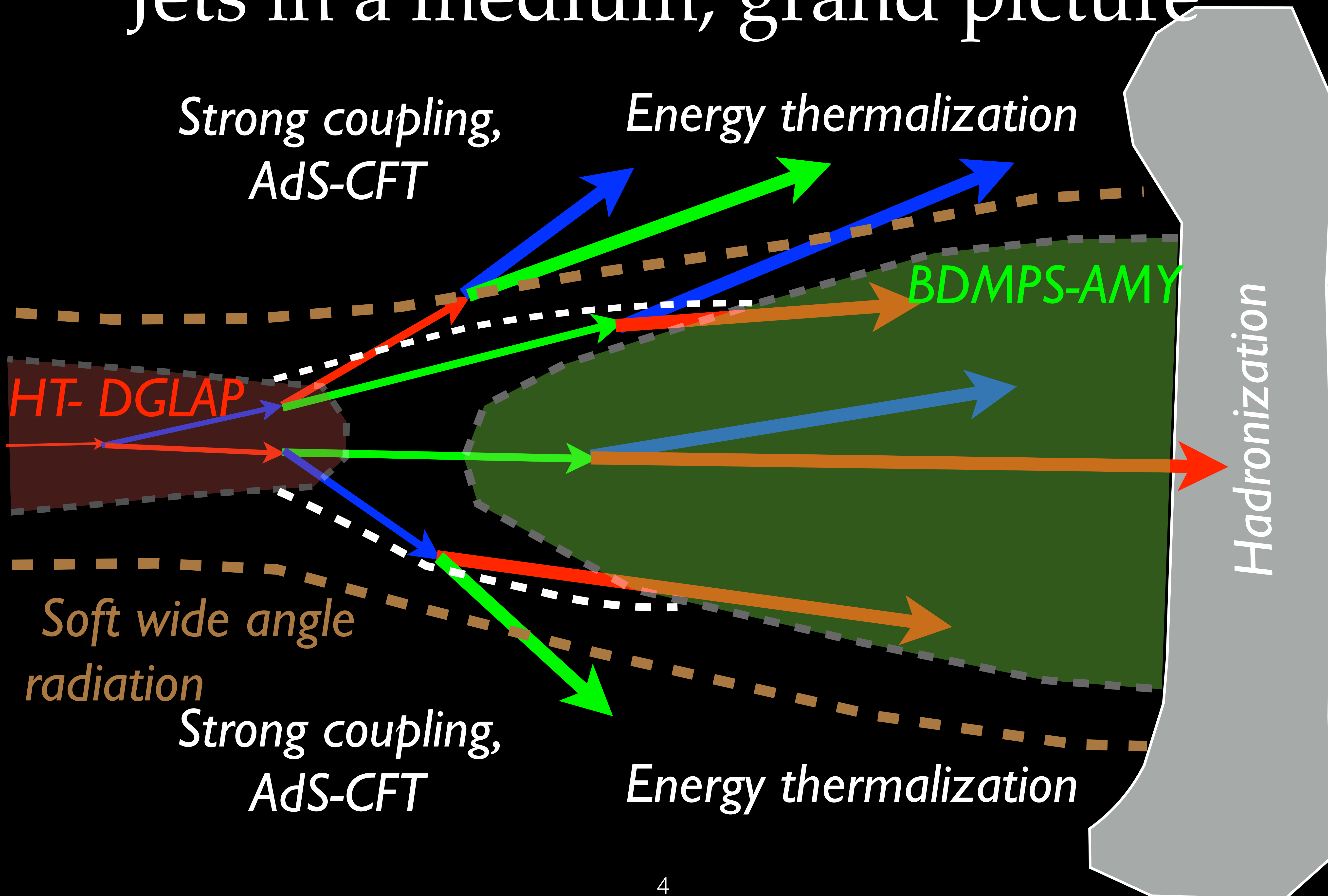
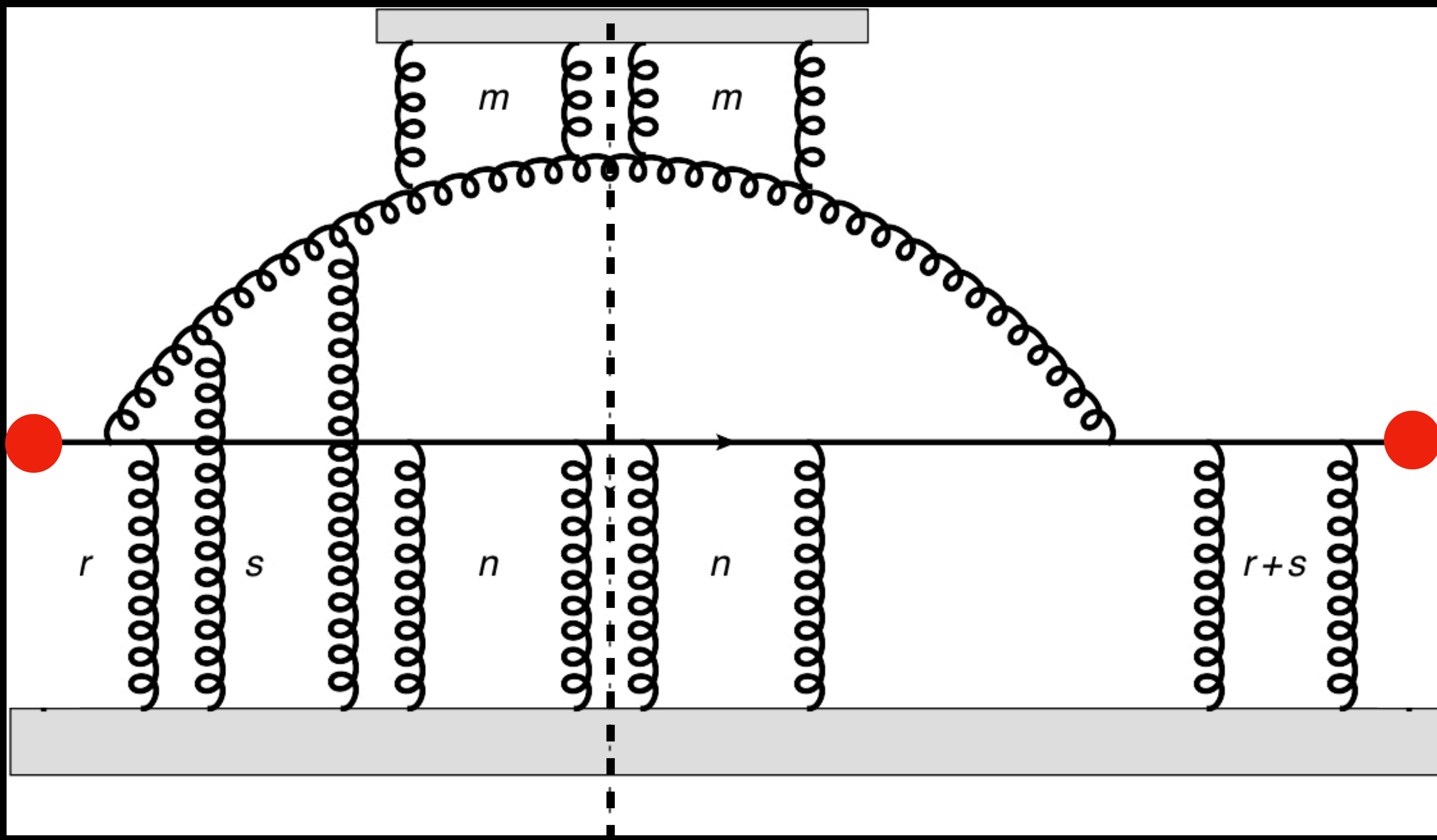


Jets in a medium, grand picture



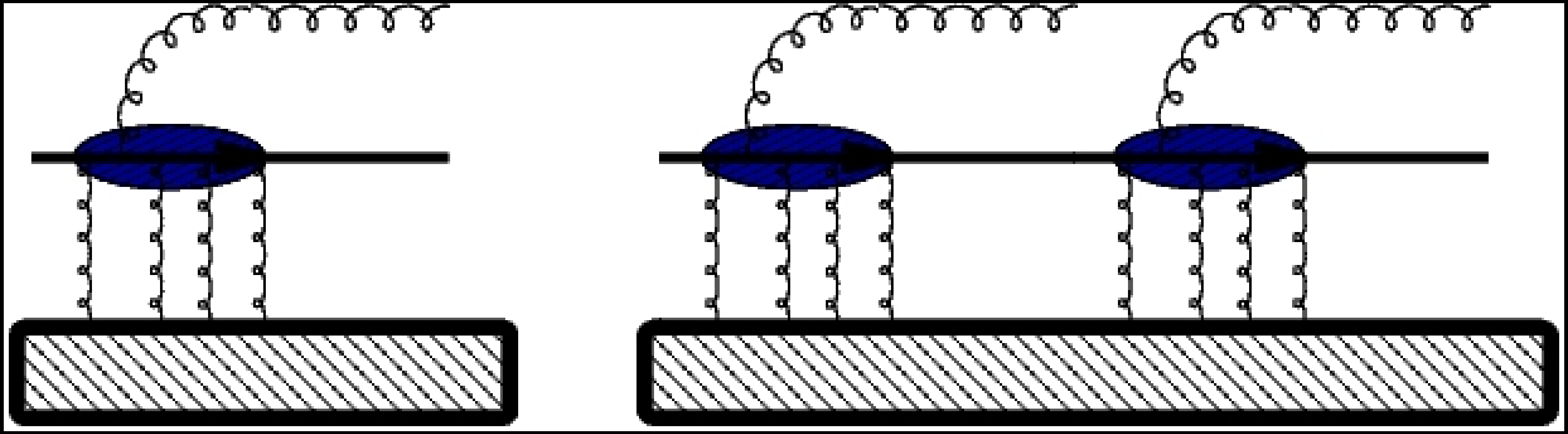
Hard sector: theoretically

Start with single gluon emission and consider multiple scattering



A.M. Phys.Rev. D85 (2012) 014023

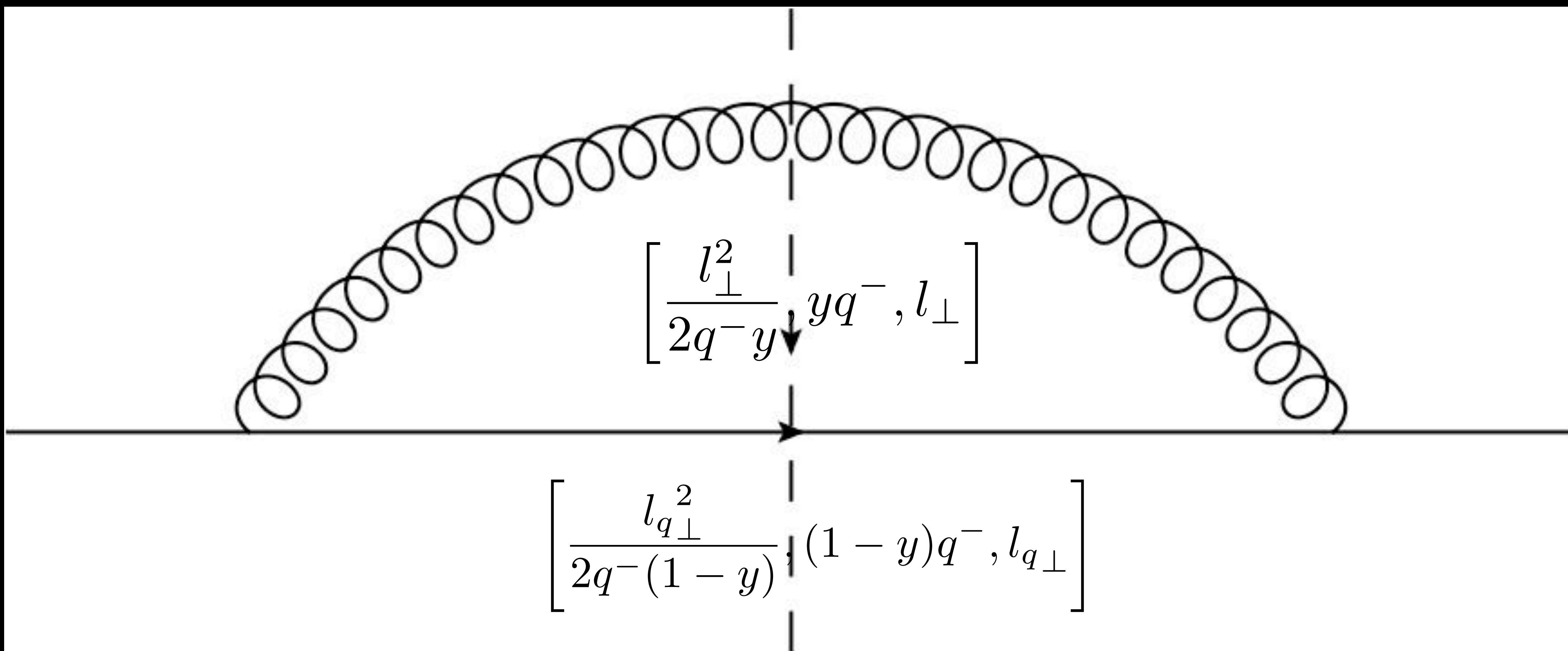
This needs to be repeated



- Usual assumption, multiple emissions are independent!

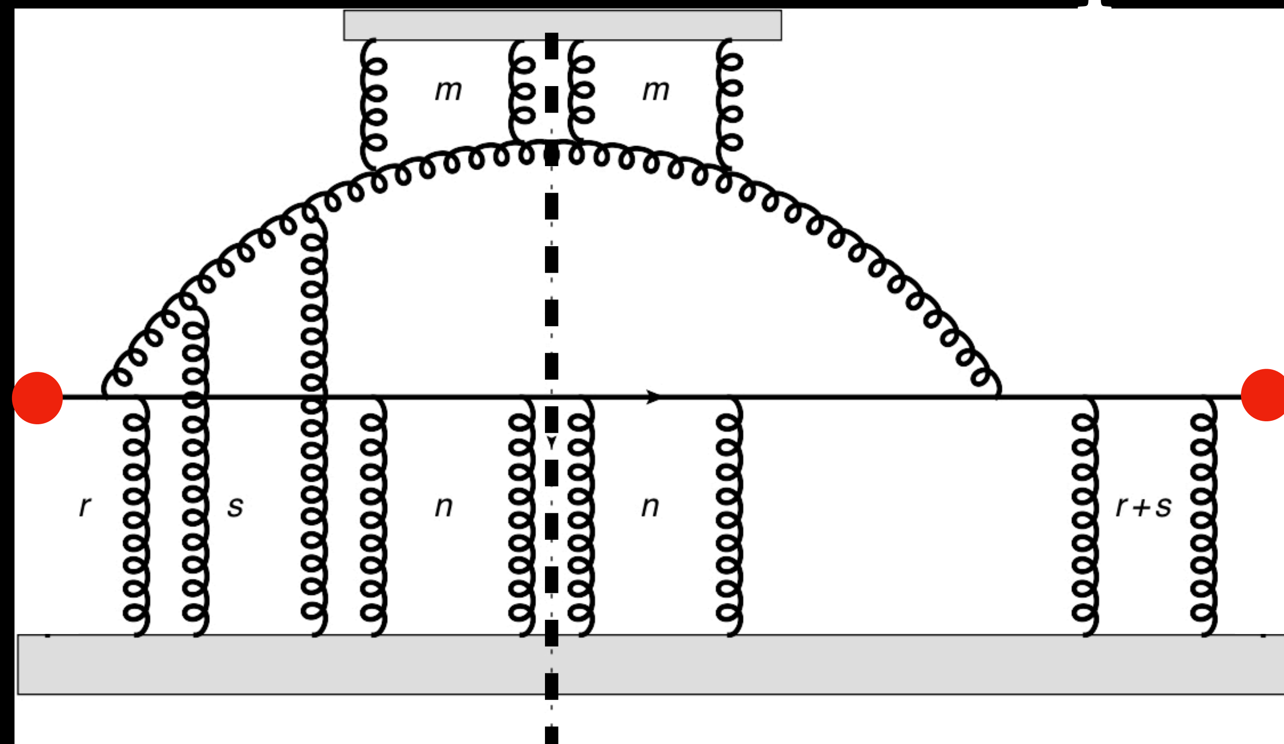
- The reason for this depends on your approximation scheme

Consider the case of one emission in vacuum



$$\sim \frac{\alpha_s C_F}{2\pi} \int dy d^2 l_\perp d^2 l_{q\perp} P(y) \frac{l_\perp \cdot l_\perp}{l_\perp^2 l_\perp^2} \delta^2(l_\perp + l_{q\perp})$$

One emission from multiple scattering



$$\int dl_\perp dl_{q\perp} dy \; \text{C.F.} \; \delta^2\left(q_\perp + l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{j=1}^{r} p_\perp^j - \sum_{l=1}^{m} k_\perp^l - \sum_{k=1}^{n} p_\perp^k\right)$$

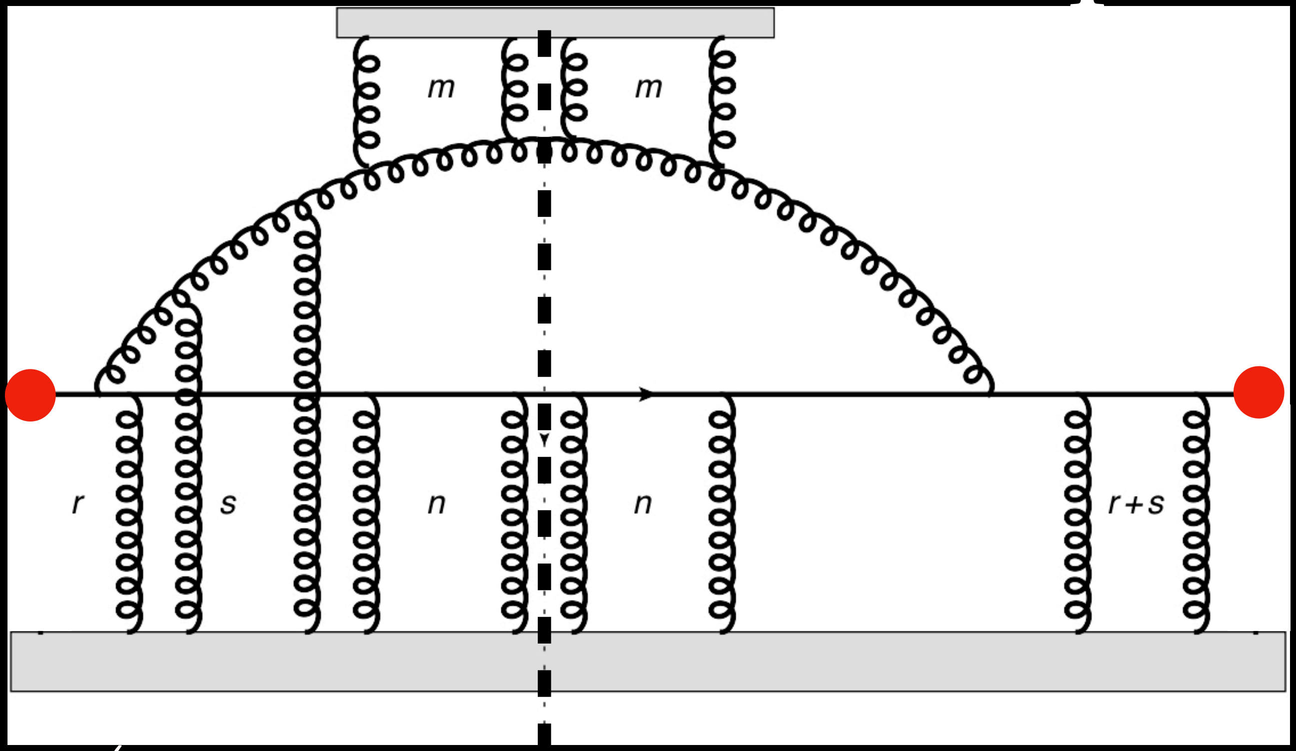
$$\frac{l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l}{\left(l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l\right)^2} \cdot \frac{l_\perp - y\sum_{i=1}^{r+s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l}{\left(l_\perp - y\sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l\right)^2}$$

$$\prod_{i=1}^{N} \int dy_i^- \frac{\int d^3\delta y_i \rho \langle p| A^+(y_i^- + \delta y_i^-, 0) A^+(y_i^-, -\delta y_\perp^i)|p\rangle}{2p^+(N_c^2-1)} e^{ik_\perp^i \delta y_\perp^i}$$

$$\left[\theta(\zeta_I^- - y_E^-)\left\{e^{-ip^+x_L y_E^-} - e^{-ip^+x_L\zeta_I^-}\right\} - \theta(\zeta_I^- - y_I^-)e^{-ip^+x_L y_I^-} - \theta(y_I^- - \zeta_I^-)e^{-ip^+x_L\zeta_I^-}\right]$$

$$\left[\theta(\zeta_C^- - y_0^-)\left\{e^{ip^+x_L y_0^-} - e^{ip^+x_L\zeta_C^-}\right\} - \theta(\zeta_C^- - y_C^-)e^{ip^+x_L y_C^-} - \theta(y_C^- - \zeta_C^-)e^{ip^+x_L\zeta_C^-}\right] \ldots$$

One emission from multiple scattering



$$\int dl_\perp dl_{q\perp} dy \text{ C.F. } \delta^2\left(q_\perp + l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{j=1}^{r} p_\perp^j - \sum_{l=1}^{m} k_\perp^l - \sum_{k=1}^{n} p_\perp^k\right)$$

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if $l_T >> k_T$, can expand in ratio

$$\frac{1}{l_\perp^2} - \frac{(1-y+y^2)\left(\sum_{i=1}^{s} k_\perp^i\right)^2}{l_\perp^4} - \frac{\left(\sum_{i=1}^{m} k_\perp^i\right)^2}{l_\perp^4} + 2(1+y^2)\frac{\left(l_\perp \cdot \sum_{i=1}^{s} k_\perp^i\right)^2}{l_\perp^6} + 4\frac{\left(l_\perp \cdot \sum_{i=1}^{m} k_\perp^i\right)^2}{l_\perp^6}.$$

$$\left[\theta(\zeta_I^- - y_E^-)\left\{e^{-ip^+x_L y_E^-} - e^{-ip^+x_L\zeta_I^-}\right\} - \theta(\zeta_I^- - y_I^-)e^{-ip^+x_L y_I^-} - \theta(y_I^- - \zeta_I^-)e^{-ip^+x_L\zeta_I^-}\right]$$
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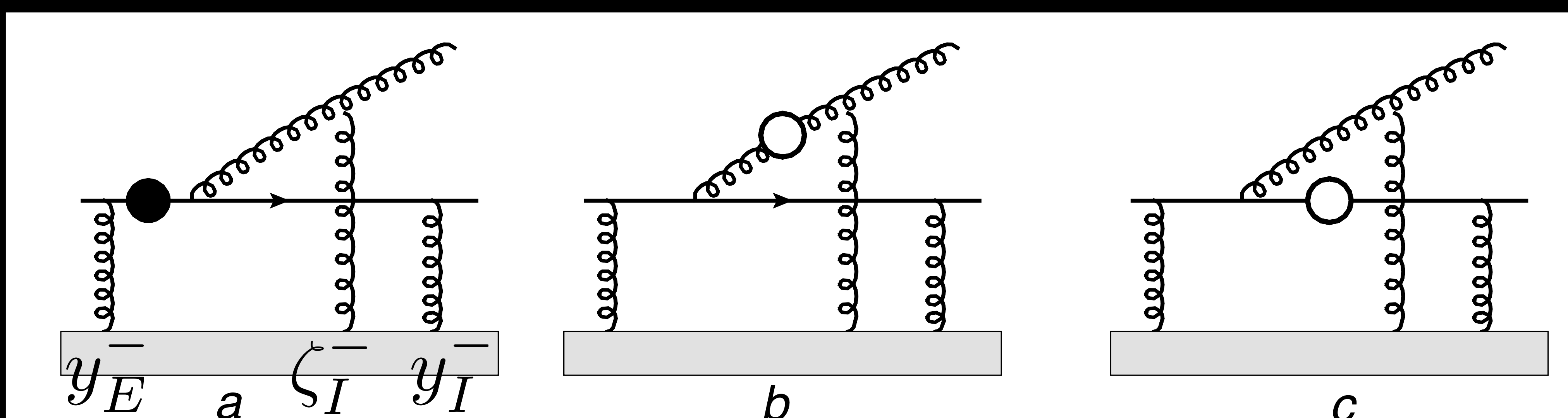


Can show that this reduces to the case of single scattering induced single emission as in Wang and Guo Nucl.Phys. A696 (2001) 788-832.

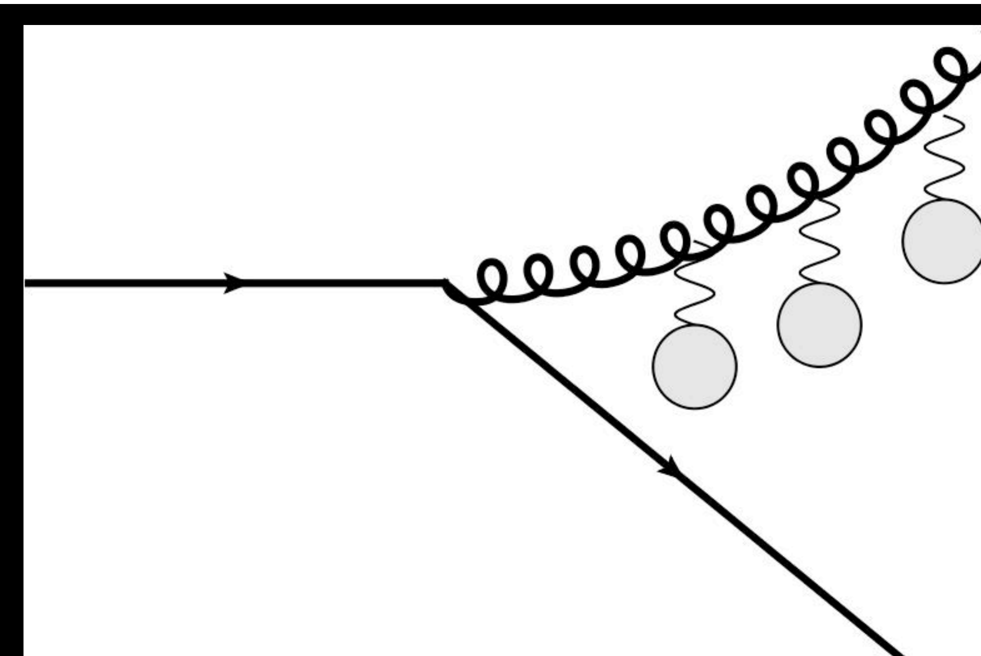
Each of these has multiple scattering

Need to use calculated double differential distribution

$$\frac{d\sigma}{dl_\perp^2\, dl_{q\perp}^2} \propto \frac{\alpha_s C_F P(y)}{l_\perp^2 y} \int_0^{L^-} d\zeta^- D(\zeta^-) \left\{2 - 2\cos\left(p^+ x_L \zeta^-\right)\right\} \left[\left(\frac{4 - 2\vec{l}_\perp \cdot \nabla_{l_{q\perp}}}{l_\perp^2}\right) \frac{e^{-\frac{l_{q\perp}^2}{4\int dy^- D(y^-)}}}{4\pi \int dy^- D(y^-)} \right.$$
$$\left. + \nabla^2_{l_{q\perp}} \frac{e^{-\frac{l_{q\perp}^2}{4\int dy^- D(y^-)}}}{4\pi \int dy^- D(y^-)} - \left(\int_{\zeta^-}^{L^-} dy^- D(y^-)\right) \left\{\frac{2\vec{l}_\perp \cdot \nabla_{l_{q\perp}} \nabla^2_{l_{q\perp}} - 4\nabla^2_{l_{q\perp}}}{l_\perp^2}\right\} \frac{e^{-\frac{l_{q\perp}^2}{4\int dy^- D(y^-)}}}{4\pi \int dy^- D(y^-)}\right]. \quad (95)$$

$l_{q\perp}$ is the off-set from the quark and gluon momenta being equal and opposite

A Monte-Carlo needed to track the momenta of each of the partons



Integrating out the $l_{q\perp}$

$$\frac{d\sigma}{dl_\perp^2} \sim \int dy \frac{\alpha(l_\perp^2) P(y)}{l_\perp^2} \int d\zeta^- \frac{\hat{q}}{l_\perp^2} \left[2 - 2\cos\left(\frac{l_\perp^2}{2q^- y(1-y)} \zeta^-\right)\right]$$

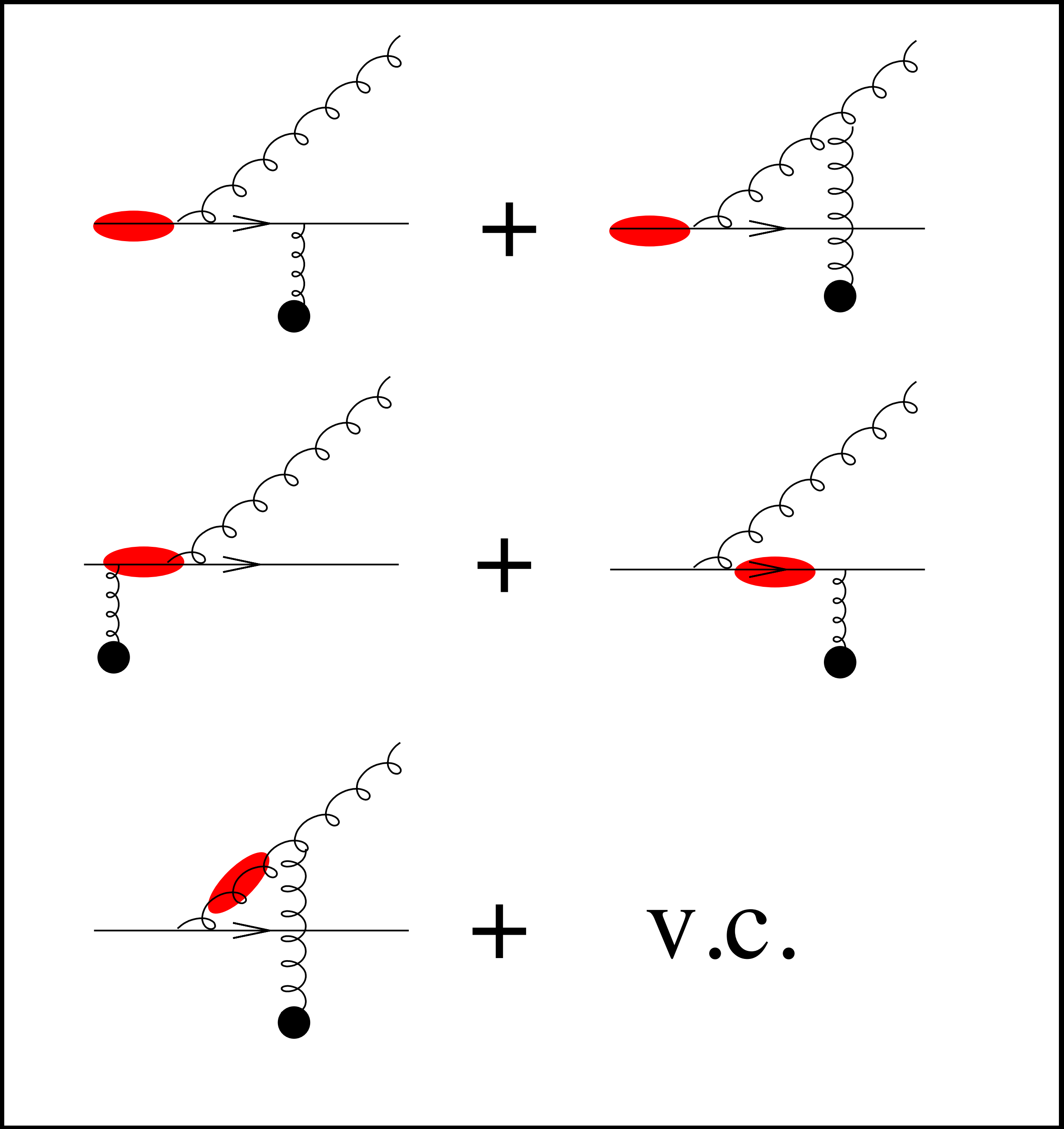
What exactly is being retained?

We are retaining terms that keep one propagator off-shell

Similar to the case of no scattering in vacuum

Introduces medium dependent correction to vacuum emission process

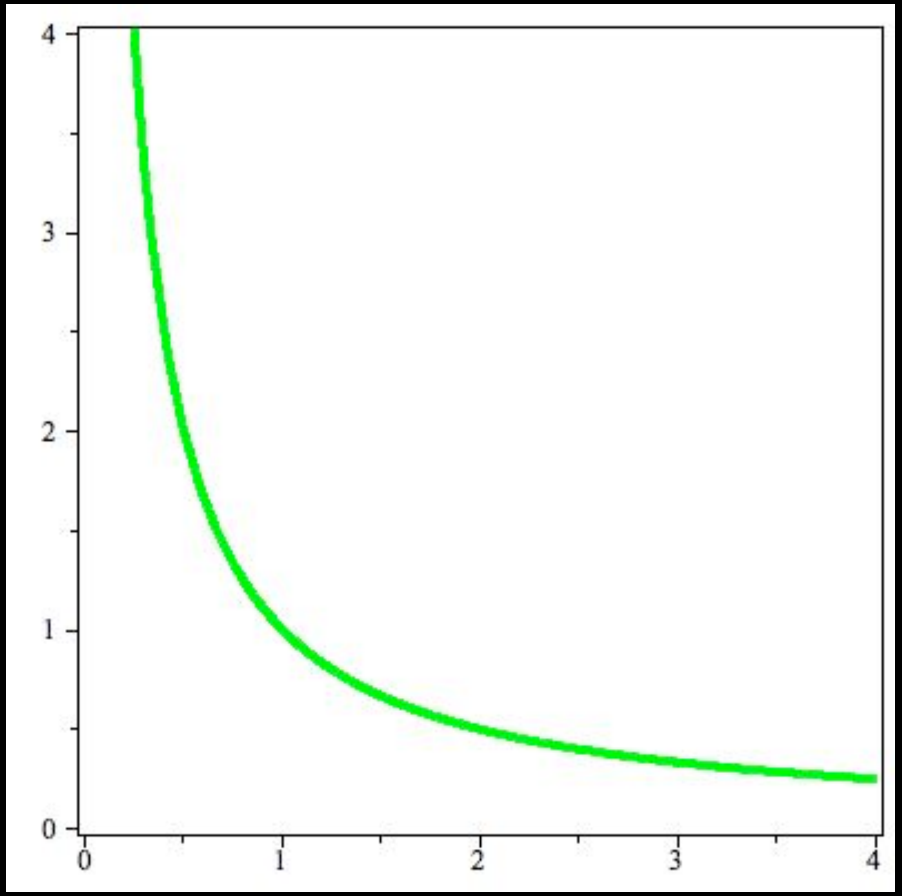
Involves interference between states of different virtuality.

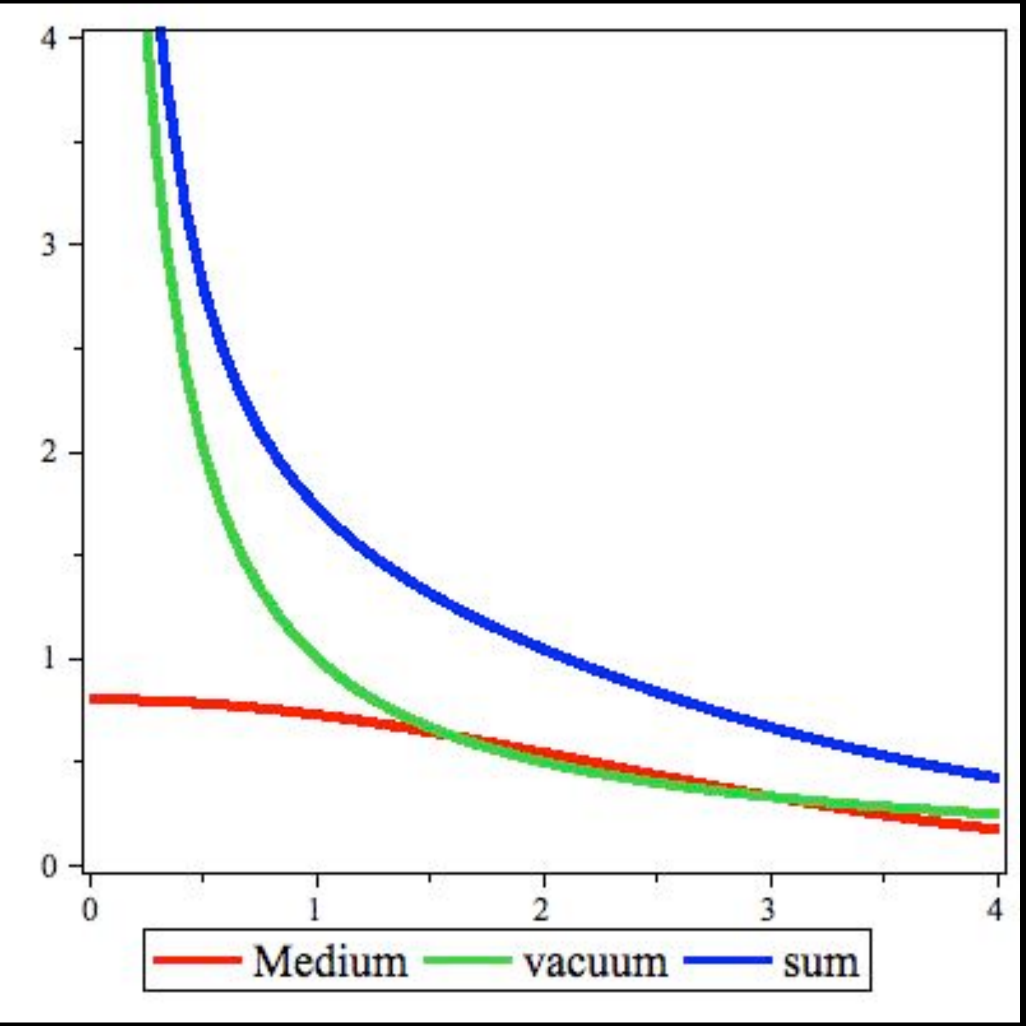


What is resummed?

Resum higher order contributions that are enhanced within the restricted phase space of the process.

$$\left[\alpha_S \sim \frac{1}{\log(Q^2)}\right] \times \int^{Q^2} \frac{dl_\perp^2}{l_\perp^2}$$





$$\left[\alpha_S \sim \frac{1}{\log(Q^2)}\right] \times \int^{Q^2} \frac{dl_\perp^2}{l_\perp^2}\left(1 + \frac{\hat{q}\tau}{l_\perp^2}\right)$$

Resummation by Differentiation: DGLAP and Sudakov form factor

Assume large scale separation from D(z) or J(z) factorization of final state and DGLAP evolution

$$\frac{\partial D(z,Q^2)}{\partial \log Q^2} = \frac{\alpha_S}{2\pi}\int \frac{dy}{y}\left[P(y)+\Delta P(y)\right]_+ D(z/y,Q^2)$$

Integral solution, by introducing the Sudakov form factor.

$$D(z,Q^2) = \Delta(Q)D(z,Q_0) + \int \frac{dQ_1^2}{Q_1^2}\frac{\Delta(Q)}{\Delta(Q_1)}\int \frac{dy}{y}\frac{\alpha_S}{2\pi}\left(\hat{P}+\Delta\hat{P}\right) D(z/y,Q_1^2)$$

Probability of no resolvable emission between Q and Q_0

$$\Delta(Q) = e^{-\int_{Q_0^2}^{Q^2}\frac{dt}{t}\int dy (P(y)+\Delta P(y))}$$

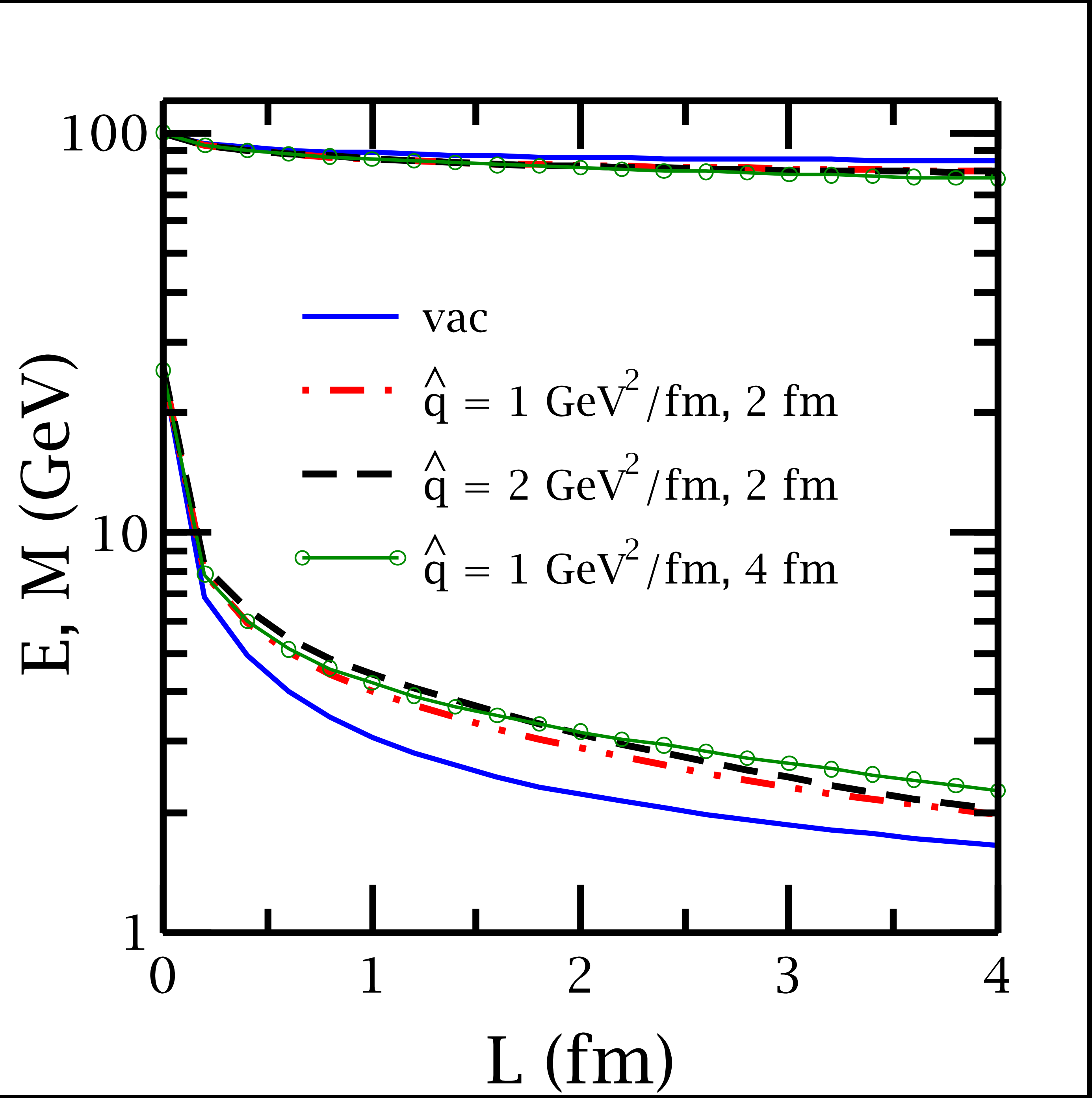
How does it affect virtuality evolution

Results from MATTER evolution

Need good eyes to see the energy loss

Scattering keeps the virtuality from dropping as in vacuum

After a certain length, virtuality is low enough to switch to another formalism



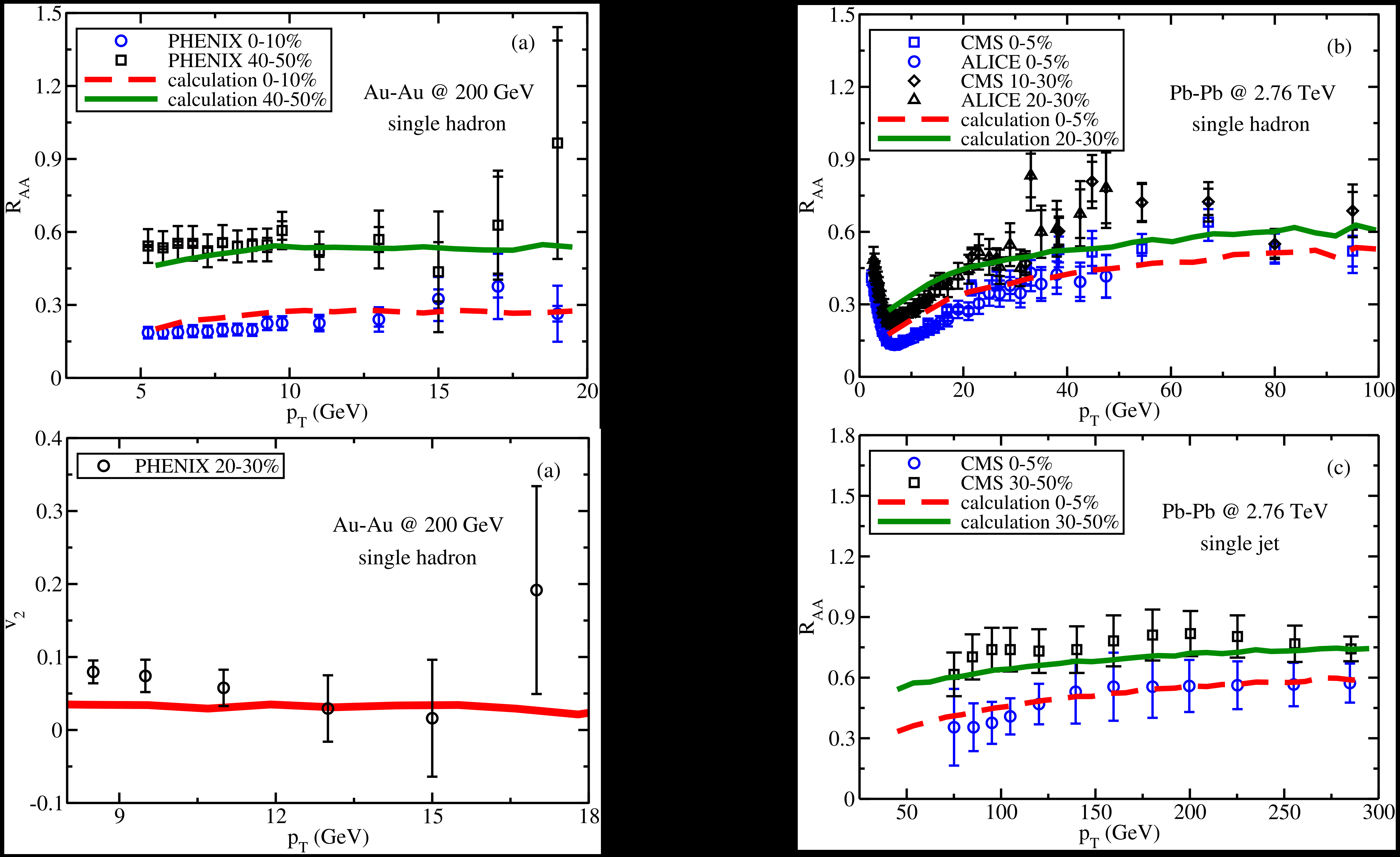
A.M. J. Putschke Phys.Rev. C93 (2016) no.5, 054909

How important is this?

- What if we only had MATTER and nothing else?
- Something needs to be done with the partons that come down to Q ~ 1 GeV.
- In vacuum: send to hadronizer
- simple model: motivated by AdS/CFT, remove partons that are more than 1fm inside QGP, when they reach Q=1GeV.
- better approximation, hand off to a low Q model.
- This could be different depending on energy of parton.

How important is this?

Hydro: VISH2+1D single shot



S. Cao, A. M. arXiv:1712.10055

Going to lower virtuality
LBT / MARTINI

$$\int dl_\perp dl_{q\perp} dy \text{ C.F. } \delta^2\left(q_\perp + l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{j=1}^{r} p_\perp^j - \sum_{l=1}^{m} k_\perp^l - \sum_{k=1}^{n} p_\perp^k\right)$$

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Transverse momentum is generated by the multiple scattering.

$$l_\perp^2 \sim \sum_i {k_i}_\perp^2 \sim \hat{q}\tau_f$$

Going to lower virtuality
LBT / MARTINI

$$\int dl_\perp dl_{q\perp} dy \text{ C.F. } \delta^2\left(q_\perp + l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{j=1}^{r} p_\perp^j - \sum_{l=1}^{m} k_\perp^l - \sum_{k=1}^{n} p_\perp^k\right)$$

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Transverse momentum is generated by the multiple scattering.

$$l_\perp^2 \sim \sum_i {k_i}_\perp^2 \sim \hat{q}\tau_f$$

Going to lower virtuality
LBT / MARTINI

Partons are now close to ``on-shell'' ~ $\hat{q}\,\tau$

Can use a Master equation to calculate the change in the distribution

The rates of changing p to p + k under multiple scattering have to be calculated

$$\frac{dP_q(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,k)}{dkdt} - P_q(p)\frac{d\Gamma^q_{qg}(p,k)}{dkdt} + 2P_g(p+k)\frac{d\Gamma^g_{q\bar{q}}(p+k,k)}{dkdt},$$

$$\frac{dP_g(p)}{dt} = \int_k P_q(p+k)\frac{d\Gamma^q_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^g_{gg}(p+k,k)}{dkdt} - P_g(p)\left(\frac{d\Gamma^g_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k-p)\right)$$

No further enhancement from phase space of radiation

emission is α_S suppressed
Thus separated by long time.

S. Jeon & G. Moore Phys.Rev. C71 (2005) 034901

The rate

The AMY rates used in MARTINI

Rates are different in LBT

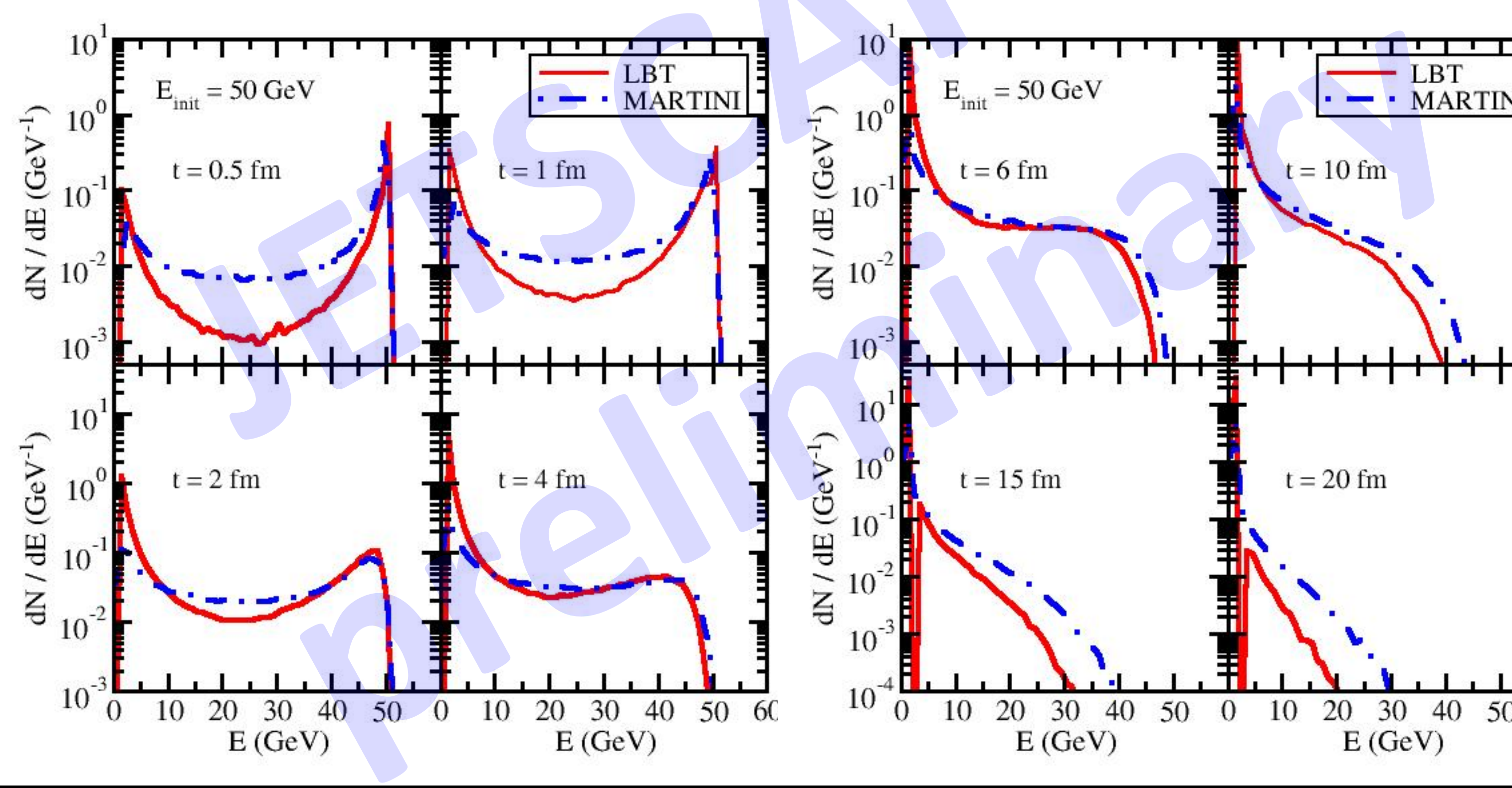
Simulation is similar.

Sample the time integrated rate of find the time when an emission occurs.

Start process after each emission

$$\frac{d\Gamma(p,k)}{dk dt} = \frac{C_s g_s^2}{16\pi p^7} \frac{1}{1 \pm e^{-k/T}} \frac{1}{1 \pm e^{-(p-k)/T}} \times$$
$$\times \left\{ \begin{array}{cc} \frac{1+(1-x)^2}{x^3(1-x)^2} & q \to qg \\ N_f \frac{x^2+(1-x)^2}{x^2(1-x)^2} & g \to qq \\ \frac{1+x^4+(1-x)^4}{x^3(1-x)^3} & g \to gg \end{array} \right\} \times$$
$$\times \int \frac{d^2\mathbf{h}}{(2\pi)^2} 2\mathbf{h} \cdot \mathrm{Re}\, \mathbf{F}(\mathbf{h}, p, k) \,,$$

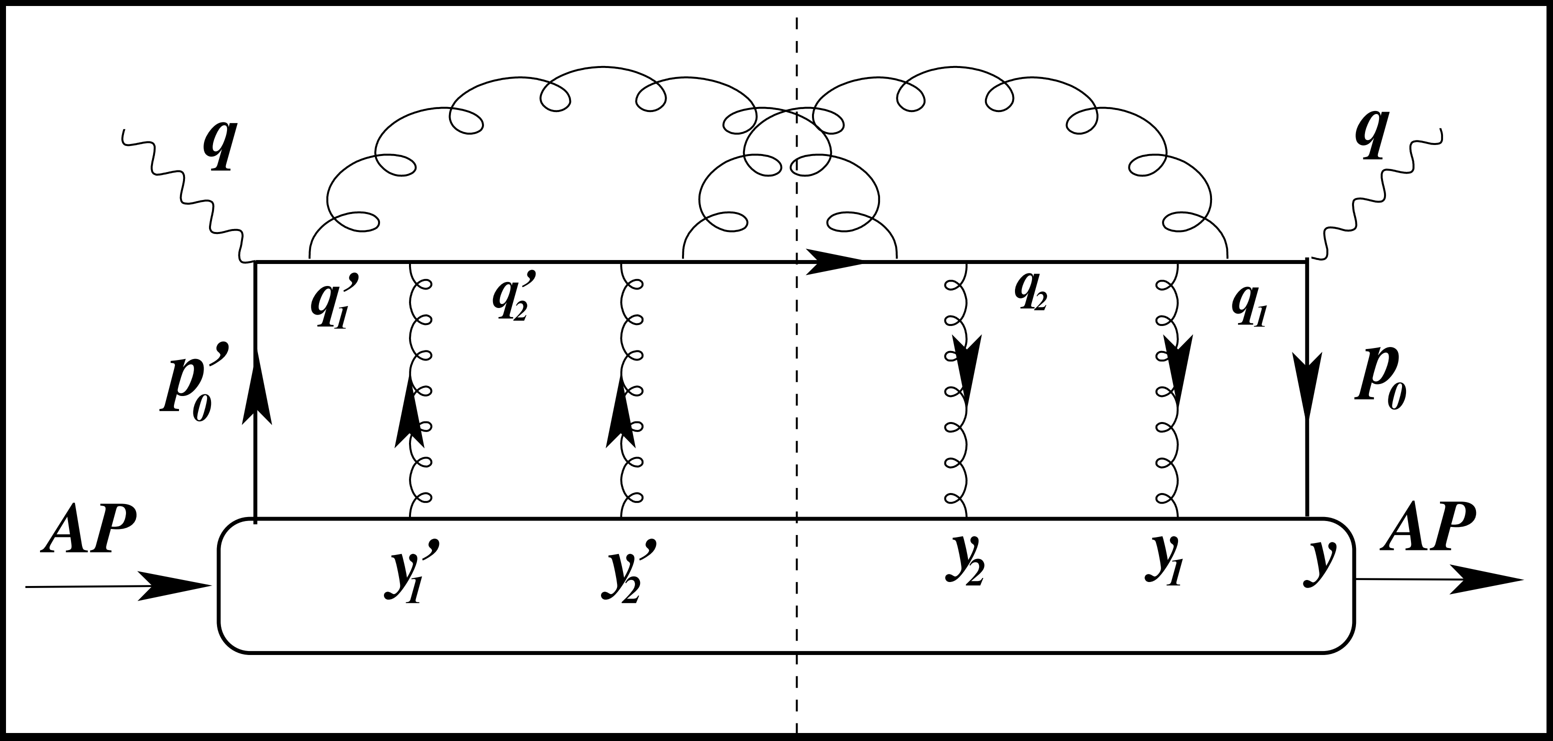
E_{init} = 50 GeV, T = 250 MeV



Curves by S. Cao and C. Park

Transitioning from one effective theory to another

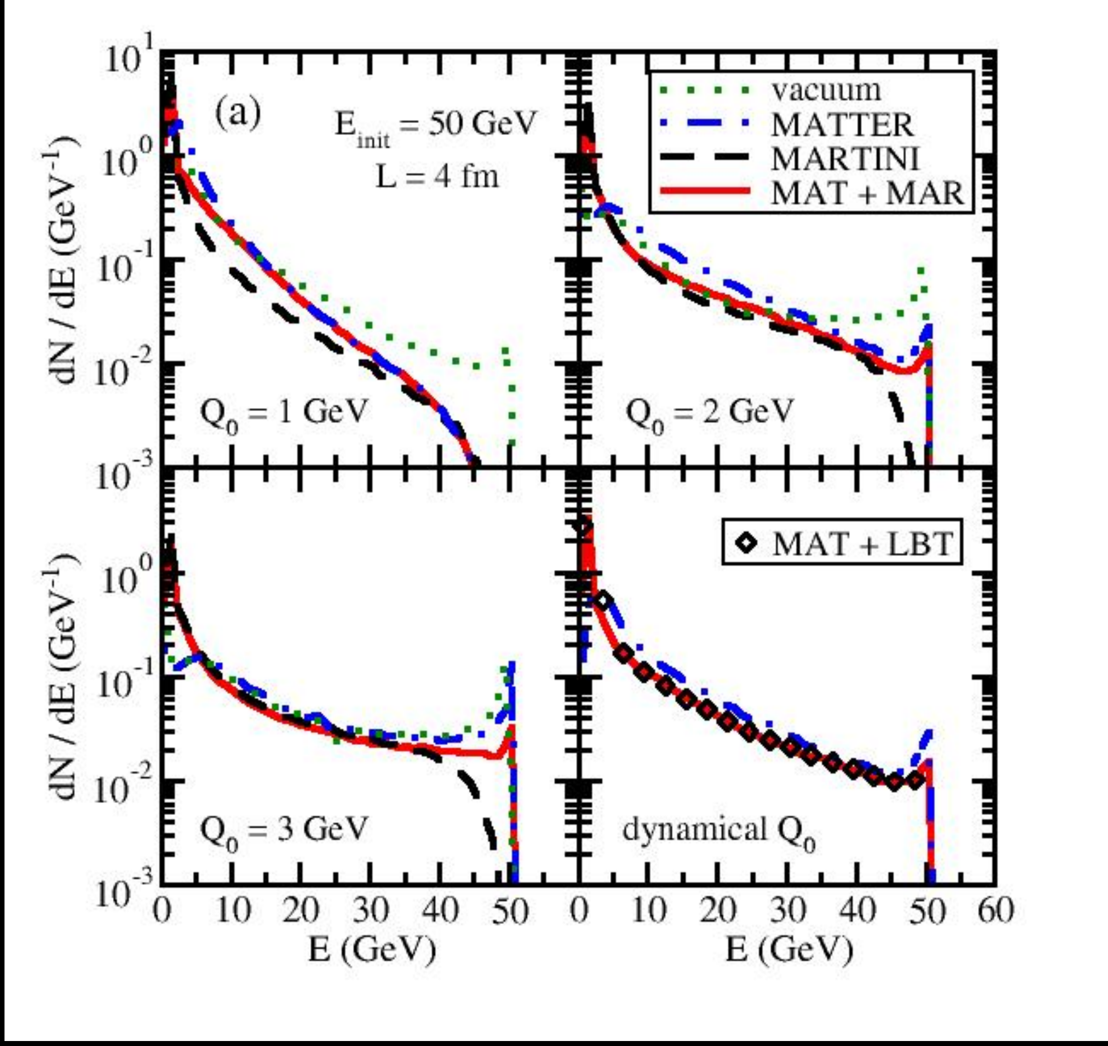
- Go to an overarching theory
- NLO: 1+2 gluon emission
- Look for regions where the leading pole dominates (HT)
- Look for regions where there is no enhancement from emission (AMY)
- Parametrically separate the two regions, and study the intermediate region



Simulating this on a parton-by-parton level is hard

- We do a sudden approximation
- Use invariant virtuality of parton to transition
- Above Q_0 use MATTER, below use MARTINI or LBT
- For $E < E_0$, use AdS/CFT.
- Interesting results for jet shape
- $2 < \hat{q}\,\tau < 3$ GeV

S. Cao (JETSCAPE) Phys.Rev. C96 (2017) no.2, 024909



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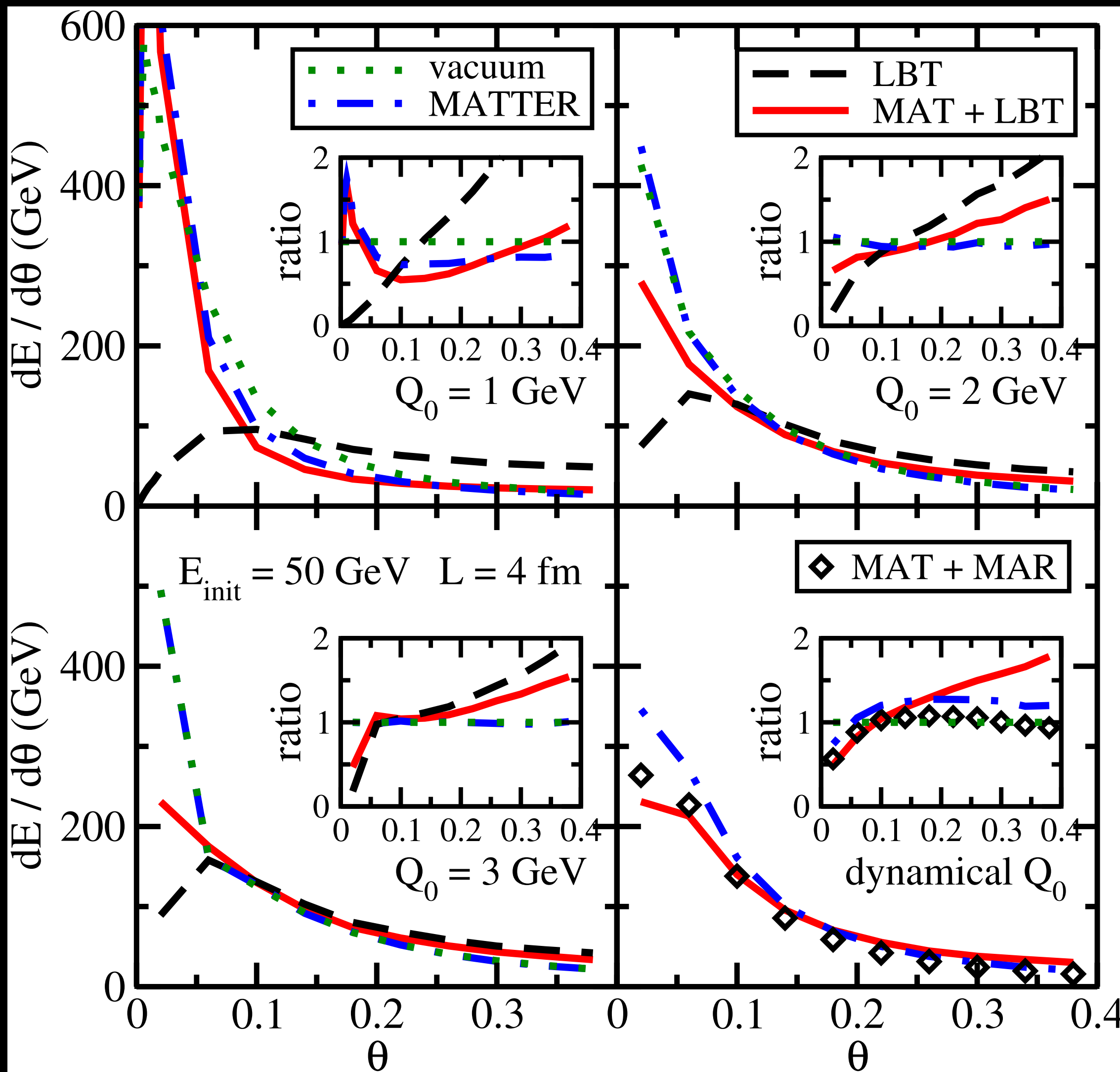
S. Cao (JETSCAPE) Phys.Rev. C96 (2017) no.2, 024909



A realistic matching calculation

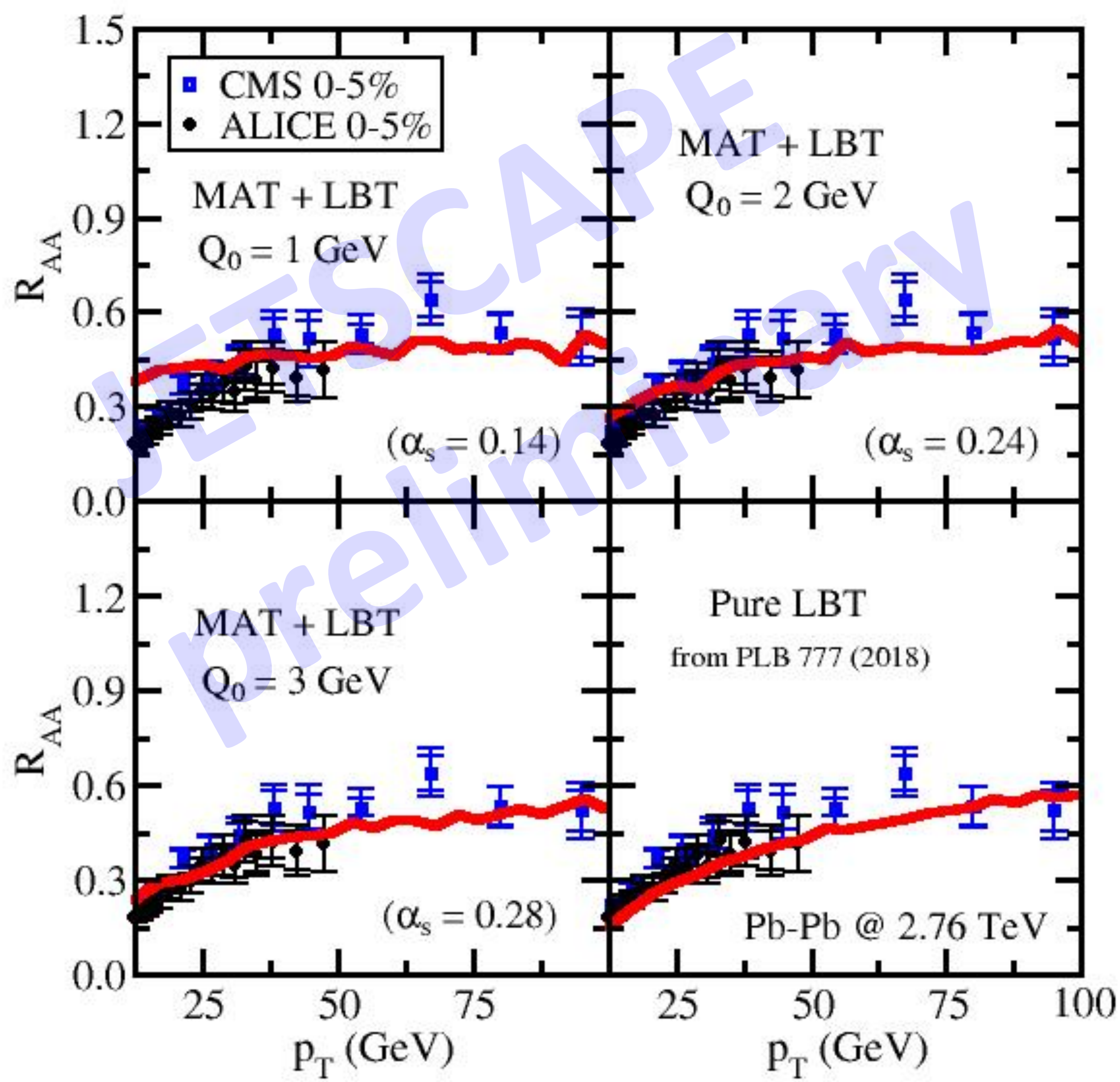
Heavy-Ion collisions are not static bricks!

$\hat{q}$ falls very quickly, much faster than $1/\tau$.

This artificially enhances the MATTER portion

There can be hotspots where $\hat{q}$ increases and then decreases

How to decide which is the right way: more observables Bayesian routines.



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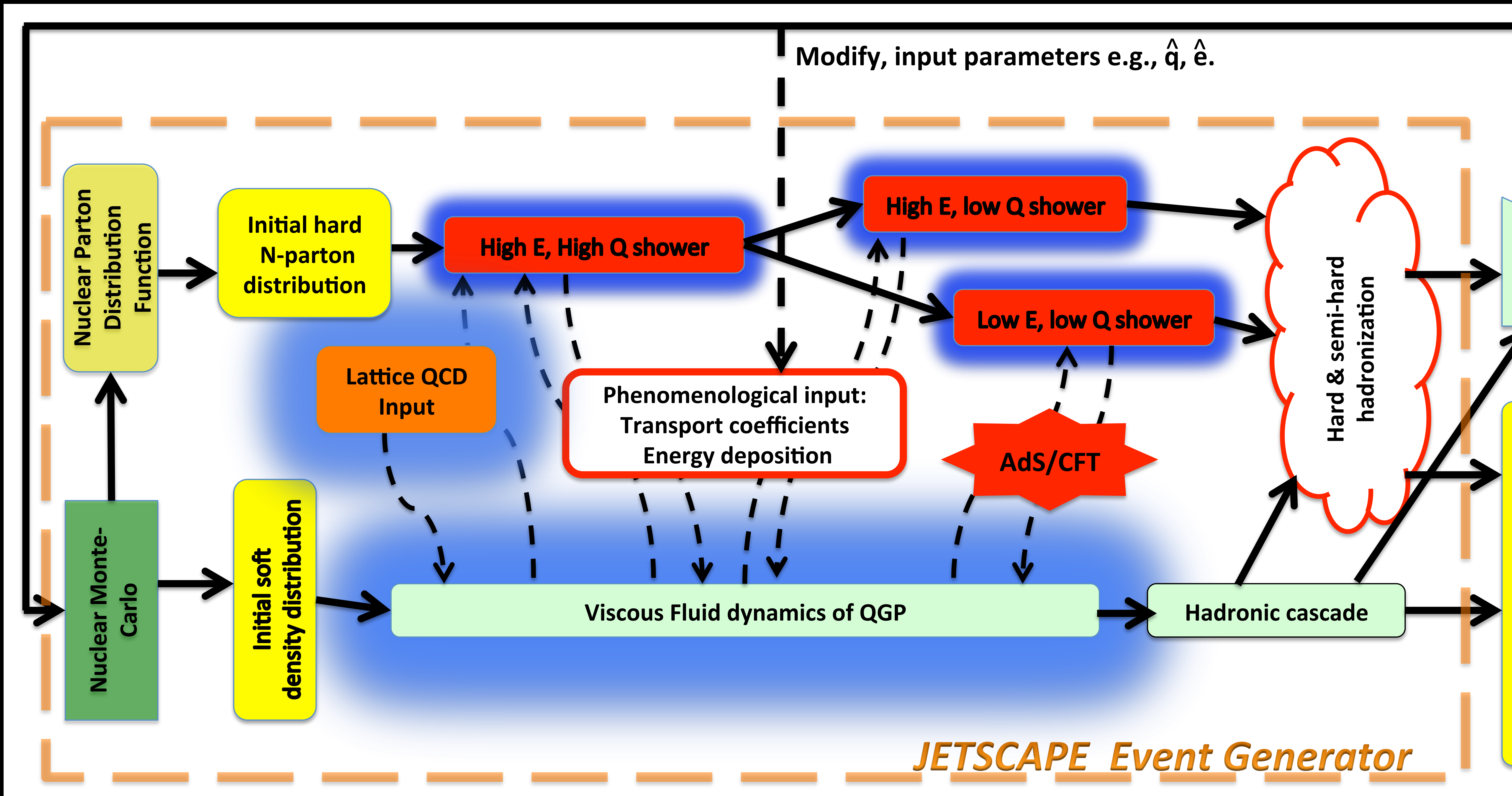

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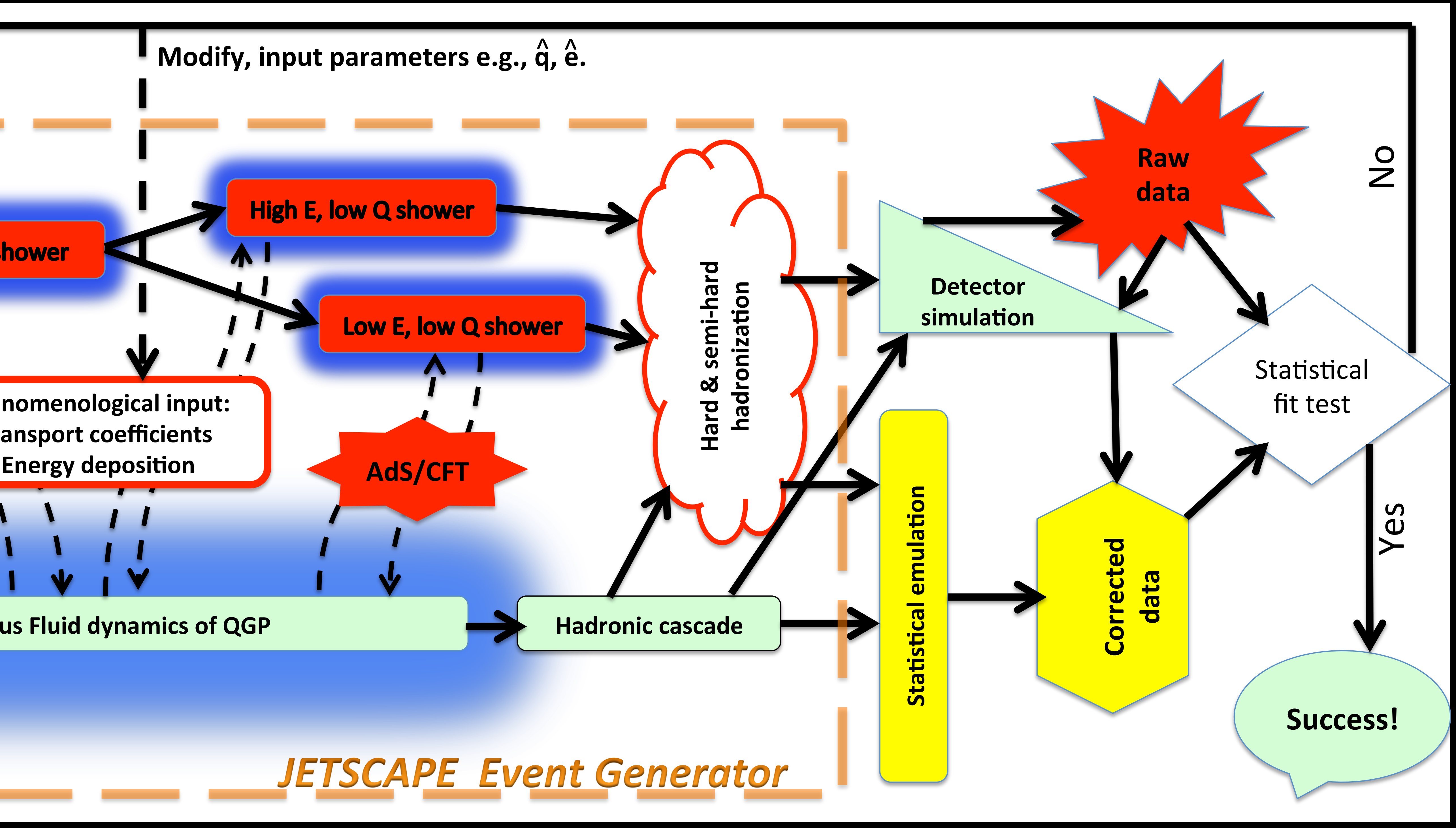
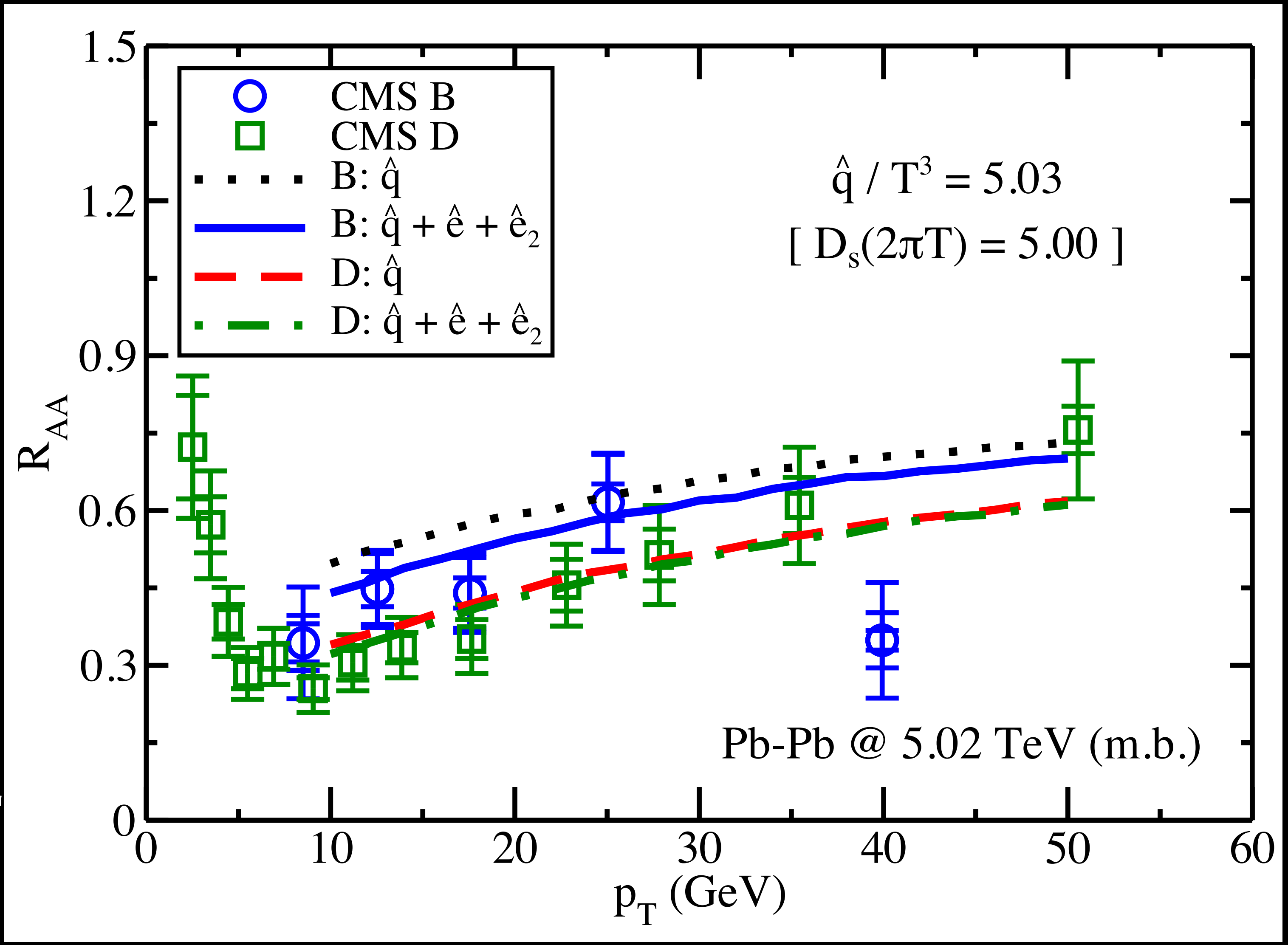


some more shameless advertisement

- Multi-Phase transport may solve the heavy-quark puzzle.
- Heavy quarks do not have a BDMPS/AMY phase
- Because of mass, semi-hard heavy quarks have a DGLAP phase followed by a Gunion-Bertsch phase
- Also heavy-quarks can radiate due to longitudinal diffusion $\hat{e}$, and $\hat{e}_2$.
- Upcoming inclusion in JETSCAPE



Summary

- Jets are multi-scale objects
- Resolve the medium at different length scales
- Behave differently at different length scales
- Different physical approaches lead to different types of MC simulation
- Some theoretical development still necessary for transition regime
- Need a sophisticated event-generator framework to study the entire set of observables
- Need extensive statistical routines and a framework to compare with experimental data.